

Recent advances on IMF research

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Abstract Here I discuss recent work on brown dwarfs, massive stars and the IMF in general, which are areas of research to which Anthony Whitworth has been contributing major work. The stellar IMF can be well described by an invariant two-part power law in present-day star-formation events (SFeVs) within the Local Group of galaxies. It is nearly identical in shape to the pre-stellar core mass function [2]. The majority of brown dwarfs follow a separate IMF. Evidence from globular clusters and ultra-compact dwarf galaxies has emerged that IMFs may have been top heavy depending on the star-formation rate density [19]. The IGIMF then ranges from bottom heavy at low galaxy-wide star formation rates to being top-heavy in galaxy-scale star bursts.

1 Introduction

The stellar IMF is the distribution function of stellar masses, m , formed together in one star-formation event (SFeV) which can be characterised by a spatial scale of up to about a pc and a stellar mass M_{ecl} . Various forms of distribution functions describing the observationally derived IMF have been proposed (e.g. [7]). According to the recent Herschel results (e.g. [2]) the SFeVs occur along thin (width of about 0.1 pc) filaments in the molecular clouds when the mass per unit length surpasses about $15 M_{\odot}/\text{pc}$. The SFeVs are deeply embedded and the star formation efficiency is $\varepsilon \approx 0.3 - 0.4$, such that about 60–70 per cent of the residual gas is blown out from them leaving the stellar population of mass $\text{few } M_{\odot} \lesssim M_{\text{ecl}}$ largely unbound. Taking the energy distribution of binary populations in observed star clusters to limit the largest density the cluster was allowed to have when it was a SFeV (too many binaries would be burned at too high densities), [18] inferred a radius-mass rela-

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tion, $R_{\text{ecl}} = 0.10 (M_{\text{ecl}}/M_{\odot})^{0.13}$, which extracts the same length scale. This suggests that the universal initial binary distribution function [17] deduced from the many observations appears to be a good representation of reality.

Remarkable progress has been achieved in constraining the form of the IMF and its variability. This progress has largely been driven by observational studies, but theoretical advances have also been many. Here a brief review is provided of the recent issues concerning the IMF, some of which are hotly debated if not poorly understood. Further details and references are to be found in the reviews by [9], [6], [4] and [17].

2 Universality of the IMF

As is evident from the reviews mentioned above, a consensus appears to have emerged in the community that the stellar IMF is largely invariant for star formation conditions as are found throughout the Local Group of galaxies at the present time. The form of this universal or canonical IMF is most simply described by a two-part power-law, $\alpha_1 \approx 1.3, 0.07 < m/M_{\odot} \lesssim 0.5$ and $\alpha_2 = 2.3, 0.5 \lesssim m/M_{\odot}$ (the "Massey-Salpeter" power-law index). This form can also be approximated by a log-normal for $m < 1 M_{\odot}$ and the same power-law part for $m > 1 M_{\odot}$ [17] but leads to a mathematically more complex object without the gain of physical reality. Concerning the origin of the IMF, [2] note the remarkable similarity between the pre-stellar core mass function and the stellar IMF, "suggesting a \sim one-to-one correspondence between core mass and star/system mass with $M_{*,\text{sys}} = \varepsilon M_{\text{core}}$ and $\varepsilon \approx 0.4$ in Aquila."

As will be seen below, the evidence that the brown dwarf IMF forms a separate distribution function which is not a continuous extension of the stellar IMF makes use of a log-normal form at low masses less attractive.

3 The brown dwarf issue

It has been known for some time that brown dwarfs (BDs) are unlikely to form from direct gravitational collapse in a molecular cloud such that the observationally deduced mass function contains a significant surplus of brown dwarfs [20, 21, 1, 13].¹ The reason is that the distribution of density maxima in a cold but turbulent molecular cloud has very few peaks which can collapse through eigengravity at the mass scale of a BD such that not much further material is accreted. Although [29, 30] argue that BDs form a continuous extension of the stellar distribution, the observational and theoretical evidence they provide strongly suggests that BDs and stars have different properties in terms of their pairing. [16] have tested the hypothesis

¹ An interesting sociological effect appears to have emerged in that authors claim good agreement with the (observed) Chabrier IMF but scrutiny of the published work shows consistently significant disagreement.

that BDs and stars follow the exact same distribution functions and exclude this hypothesis with very high confidence. The various flavours of BDs that can in principle arise (collisional, photo-evaporated, ejected embryos) have been discussed [15] with the result that in the present-day star-forming conditions mostly the ejected embryo flavour dominates. The original suggestion of this scenario has been updated by [23, 24, 5] by the argument that the gravitationally pre-processed material in outer accretion disks is able to cool sufficiently rapidly upon compression to allow direct gravitational collapse at the BD mass scale. The resulting IMF of BDs compares remarkably well with the observationally deduced BD IMF ($\alpha_0 \approx 0.3$). The resulting binary properties of BDs are also accounted for naturally [24].

The BD IMF is thus a nearly flat power-law from the opacity limit for fragmentation ($m_l \approx 0.01 M_\odot$) to an upper limit which transgresses the hydrogen burning limit. In principle, arbitrarily massive "BDs" can form in very massive disks around massive stars such that here the origin of stars vs BDs becomes blurred. Because massive stars are exceedingly rare the stellar population formed through this disk-fragmentation channel is negligible in comparison to the "normal" stellar population which results from direct molecular cloud fragmentation.

Thus in order to correctly account for a stellar population with BDs most of the BD population must be added in terms of a separate distribution function, as is also the case for planets which follow their own mass distribution. The BD IMF can be expressed as a nearly flat power-law with a continuous log-normal extension from the stellar regime being ruled out.

4 Variation of the IMF

A hint at a possible variation of the IMF in the MW has emerged due to present-day star-formation events possibly producing more low-mass stars than previously. This has been quantified as a metallicity dependence, $\alpha \approx 1.3 + 0.5[\text{Fe}/\text{H}]$ [17]. From the study of massive elliptical (E) galaxies, it has emerged that the IMF must have been significantly bottom heavy. [8] inferred $\alpha = 3.41 + 2.78[\text{Fe}/\text{H}] - 3.79[\text{Fe}/\text{H}]^2$ (for $0.1 \lesssim m/M_\odot \lesssim 100$, although not explicitly stated in the paper) and a more recent analysis by [25] also suggests an increasingly bottom heavy IMF with increasingly massive E galaxies. This may be related to the postulated cooling-flow-accretion population of low-mass stars [14].

5 The massive end of the IMF

[28] had already suggested that massive stars may preferentially form in shocked gas. As reviewed in [17] there has been much observational evidence for top-heavy IMFs in star-bursts. As these are observationally unresolved, this evidence was indirect and largely ignored. Observations of the assembly of the stellar population

over cosmological epoch have also been pointing to top-heavy IMFs in the past, as otherwise there would be more low-mass stars locally than are observed. Three independent more-direct lines of evidence for the IMF becoming top-heavy with star-formation rate density have recently emerged:

First: It is well known that ultra-compact dwarf galaxies (UCDs), which have a mass scale of $10^6 - 10^8 M_\odot$, have larger dynamical mass-to-light (M/L) ratios than normal stellar populations. This is unlikely due to exotic dark matter as the phase-space available in UCDs would not accommodate significant amounts of dark matter. Instead, a top-heavy IMF would have lead to an overabundance of stellar remnants in UCDs which would enhance their dynamical M/L ratios. Thus, the variation of the required $\alpha_3, m > 1 M_\odot$, can be sought to explain the dynamical M/L ratios [10].

Secondly: UCDs have an overabundance of low-mass X-ray bright sources (LMXBs). In globular clusters (GCs), LMXBs are known to be formed from the dynamical capture of stars by stellar remnants mostly in the core of the GCs. As the star evolves the remnant accretes part of the star's envelope thus becoming detectable with X-rays. The LMXB population is constantly depopulating and needs to be replenished by new capture events. Indeed, the theoretically expected scaling of the fraction of GCs with LMXB sources with GC mass is nicely consistent with the observed data assuming an invariant stellar MF. Applying the same theory to UCDs uncovers a break-down of this agreement as the UCDs have a surplus of LMXB sources. By adding stellar remnants through a top-heavy IMF when the UCDs were born, i.e. by allowing α_3 to vary with UCD birth mass, consistency with the data can be sought [11].

Thirdly: Low-concentration GCs have been found by de Marchi et al. (2007) to be depleted in low mass stars while high-concentration GCs have a normal MF. This is contrary to the energy-equipartition driven depopulation of low mass stars because more concentrated clusters ought to have lost more low mass stars. It is also not consistent with any known theory of star formation, because the low-concentration clusters typically have a higher metallicity which would, if anything, imply a surplus of low-mass stars. The currently only physically plausible explanation is to suppose that the young GCs formed compact and mass segregated and that the expulsion of residual gas unbound a part of the low-mass stellar population. By constraining the necessary expansion of the proto-GCs (i.e. SFeVs), correlations between metallicity, α_3 and tidal field strength emerge which constrain the very early sequence of events that formed the Milky Way as well as the dependency of α_3 on density and metallicity of the SFeV [19].

Putting this all together, a consistent variation of α_3 with density and metallicity of the SFeVs emerges: for $m > 1 M_\odot, x \geq -0.89$: $\alpha_3 = -0.41x + 1.94$ with $x = -0.14[\text{Fe}/\text{H}] + 0.99\log_{10}(\rho_6)$, where $\rho_6 = \rho/(10^6 M_\odot \text{pc}^{-3})$ and ρ is the density in M_\odot/pc^3 .

Thus, SFeVs at a star-formation rate density $SFRD < 0.1 M_\odot/(\text{pc}^3 \text{Myr})$ can be assumed to have an invariant IMF with $\alpha_3 = \alpha_2$ (subject to the possible variation with metallicity discussed above), while SFeVs with larger SFRDs tend towards top-heavy IMFs whereby the trend is enhanced at lower-metallicities.

6 Massive stars and the IGIMF

The formation of massive stars is notoriously difficult to study because they are rare and deeply embedded. Thus, much fiction can be associated with the formation of massive stars and the only well-posed approach to ascertain a hypothesis is to test its consequences against data taking care to note that by showing one hypothesis to work does not exclude another hypothesis.

There are two major competing hypothesis:

According to the one hypothesis the IMF may be taken to be a probability distribution function such that the stellar ensemble in a whole galaxy is always a random draw from the stellar IMF. This allows massive stars to form in isolation as rare events.

The other hypothesis is related to optimal sampling [17] according to which the stellar IMF is a distribution function which scales with M_{ecl} such that the most massive star, m_{max} , in the SFEV follows a $m_{\text{max}}(M_{\text{ecl}})$ relation [26]. The total star-formation rate (SFR) of a galaxy follows from all its SFEVs, such that a large SFR implies SFEVs that reach to large masses and thus to large SFRDs which then imply top-heavy IMFs in these. As a consequence the IMF of a whole galaxy (the "integrated IMF" = IGIMF) is steeper (larger α_3), or flatter (i.e. top-heavy) than Massey-Salpeter, depending on its SFR. The implications for the astrophysics of galaxies as well as for cosmology are major.

The vast quantity of data are consistent with the latter theory, and most data can most simply and naturally be explained within the IGIMF framework [22, 27]. A counter-argument against the IGIMF theory often put up, namely that evidence exists that massive stars can form in isolation, is countered by the observed fraction of massive stars deemed to have formed in isolation being smaller than the fraction of apparently isolated massive stars if all massive stars in fact do form in embedded clusters, and by virtually all best-candidates for isolated massive star formation having been shown to be most likely stemming from clusters [12].

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